The Largest Superfluid Gaps in Nature and in the Laboratory

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Theorists in Los Alamos predicted that the largest pairing gap would be found in cold atom experiments with trapped ^{6}Li atoms [1]. In cold atom experiments it is possible to adjust the strength of the interaction, and in particular to tune the interaction so that two isolated particles would be on the threshold of being bound—the so-called unitary regime where the scattering-length between particles becomes infinite. Consequently, in the unitary regime the only physical scale in a many-particle system is the Fermi momentum or the inverse inter-particle distance. All physical quantities, including the ground-state energy and the pairing gap, must be universal constants times the Fermi energy of the non-interacting system. Previously, LANL theorists had predicted the ground-state energy, and this result has been confirmed by experimentalists at MIT, Rice, and Duke universities.

LANL researchers had also predicted the pairing gap in cold atoms at unitarity to be half the Fermi energy. This is in stark contrast to traditional superfluids and superconductors, where the pairing gap is thousands of times smaller than the Fermi energy. However, a direct and unambiguous method to measure the superfluid-gap in cold-atom experiments did not exist. To address this problem, Carlson and Reddy analyzed the polarization measurements performed by the MIT group [2] and showed that it can provide very stringent lower and upper bounds on the value of the pairing gap.

By trapping and cooling ^{6}Li atoms in two different hyperfine states (labeled spin-up and spin-down) the MIT team was able to observe phase-separation between a superfluid inner-core region with nearly equal spin-up and spin-down particles, and a highly polarized normal state in the outer shell with different spin-up and spin-down densities. The two regions were separated by a first-order transition. Amazingly, in the vicinity of the interface the superfluid phase carried a sizeable polarization at low but finite temperatures (Fig. 1). LANL theorists have analyzed these experiments and found this polarization near the interface is in good agreement with quantum Monte Carlo predictions for the equation of state and the pairing gap. Figure 1 shows the comparison of theoretical results with experimental

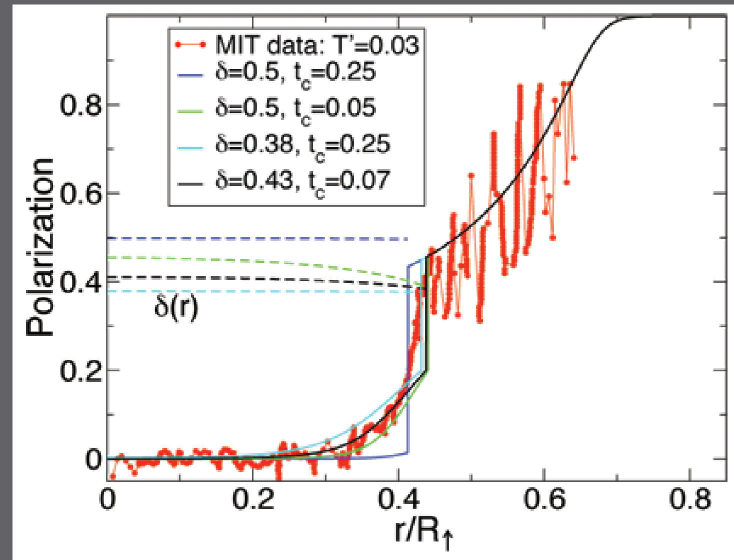

Fig. 1. Theoretical predictions for the pairing gap for neutron matter and cold atoms as a function of density or coupling strength.

measurement of the polarization density as a function of the radius of the atomic trap. The polarization of the superfluid in the vicinity of the transition located at r ~0.4 requires a superfluid gap in the range of 0.4-0.5 times the Fermi energy. This is dramatically larger than any other fermionic system measured in the laboratory.

Going beyond the laboratory, the largest pairing gap in nature can be found in the exotic astrophysical environments of neutron stars. The interaction between two neutrons is nearly strong enough to bind them, and is therefore quite similar to cold atoms in the unitary regime. In ordinary nuclei, the range of the interaction is comparable to the inter-particle spacing, and the pairing gap is ‘only’ about 10 percent of the Fermi energy. LANL researchers have examined the equation of state and the pairing gap in low-density neutron matter, as occurs in the crusts of neutron stars. The equation of state is found to be exceedingly close to that of cold atoms. The pairing gap is shown in Fig. 2. It is large, but reduced somewhat compared with cold atom gas because of the finite range of the interaction. LANL

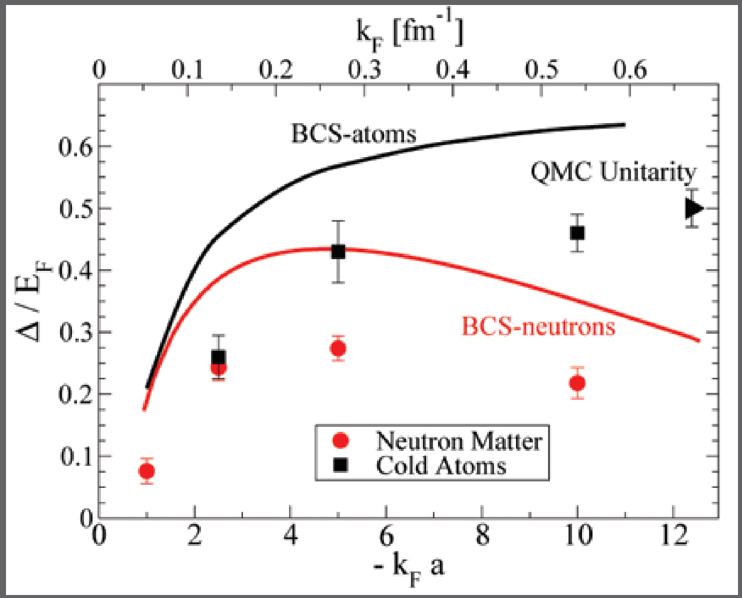

Fig. 2. Polarization versus radius observed in the cold-atom experiment. Comparison between LANL theory and the MIT experiment yields stringent lower and upper bounds on the gap.

researchers find a maximum gap of around 30 percent of the Fermi energy for neutron stars. The gap is also very large compared with the typical temperature inside neutron stars, rising to a maximum of 2 MeV. This large gap can be a very important in astrophysics, affecting the cooling rates of neutron stars. Similar large gaps may also occur in the inner cores of neutron stars where deconfined quarks can form Cooper pairs. The excellent agreement between theory and experiment in the cold-atom context lends credence to extrapolating theory to strongly interacting Fermi systems in neutron stars.

These strongly interacting Fermi systems also provide a rich opportunity to search for exotic states of matter including so-called gapless superfluids, where the groundstate is simultaneously polarized and superfluid. Indeed, LANL researchers have predicted this state will occur at even stronger interactions, where two particles in a vacuum would be slightly bound. Experimentalists are presently searching for this phase of matter.

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[1] J. Carlson and S. Reddy, *Phys. Rev. Lett.*, **96,** 060401 (2005).
[2] Y. Shin et al., arXiv:0709.3027v2 (2007).
[3] J. Carlson and S. Reddy, arXiv:0711.0414v2, accepted by *Phys. Rev. Lett.* (2008).
[4] A. Gezerlis and J. Carlson, *Phys. Rev. C* **77**, 032801 (R) (2008).

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